ADTEC

RESEARCH STUDY INTO THE NEAR EARTH APPLICATION
OF MILLIMETER RADIO WAVES AS APPLIED TO
CERTAIN BATTLEFIELD PROBLEMS

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Special Technical Report
on
Work Assignment #4

ADVANCED TECHNOLOGY CORPORATION
1830 York Road
Timonium, Maryland

December 15, 1967

Ballistic Research Laboratories
Aberdeen Proving Ground, Maryland
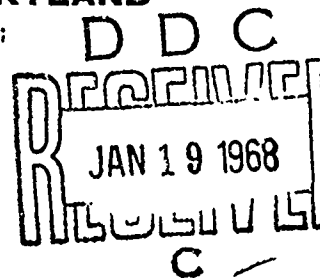Contract No. DA-18-001-AMC-829(X)

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ABSTRACT

This report concerns a brief study made of the applicability of Luneberg lenses to a scanning antenna system at 35 GHz. The study showed the applicability of the approach for certain situations, but for the specific requirements of the desired application, the use of the Luneberg lens was inappropriate. The system required 35° steering of a 35 GHz pencil beam formed by a 36" diameter aperture. The combination of aperture size and frequency leads to a currently prohibitive materials requirement. Alternative approaches using phase shifter techniques and non-resonant slot arrays are discussed.

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1. INTRODUCTION AND BACKGROUND

The purpose of this brief study was to investigate the application of a Luneberg lens to the mechanical steering of two synchronized 15 GHz antenna beams. The beams were to scan two contiguous 35 degree sectors. Further requirements on the system toward which this study was particularly pointed were that the system be capable of helicopter borne operation, and that the gain be high.

The decision to investigate Luneberg lenses for this application was arrived at through a logic essentially as follows. The problem of steering an antenna beam through 35° with no appreciable change in beam shape or width is not trivial. There exists, of course, the standard radar approach of swinging the entire aperture and feed assembly through the desired angles, but we shall assume in the discussion that follows that an alternate approach is desired which will move less size and mass. Beam steering through small angles can be accomplished by feeding a parabolic reflector or a lens through a small range of angles near the geometric axis. A $\pm 17\text{-}1/2^{\circ}$ requirement, however, is not compatible with this technique, since the distortion becomes too great over these large deviations.

One possibility for consideration is a system which only illuminates a portion of the main aperture. Consider a Cassegrain system wherein the small reflector is movable about an axis. he reflector shapes and sizes could be properly chosen such that the beam would be steerable over the angles desired. If, however, one is considering a 36" effec ive aperture as an ultimate application, this would lead to a rather large and expensive parabola, and could only be used to furnish one of the two beams desired.
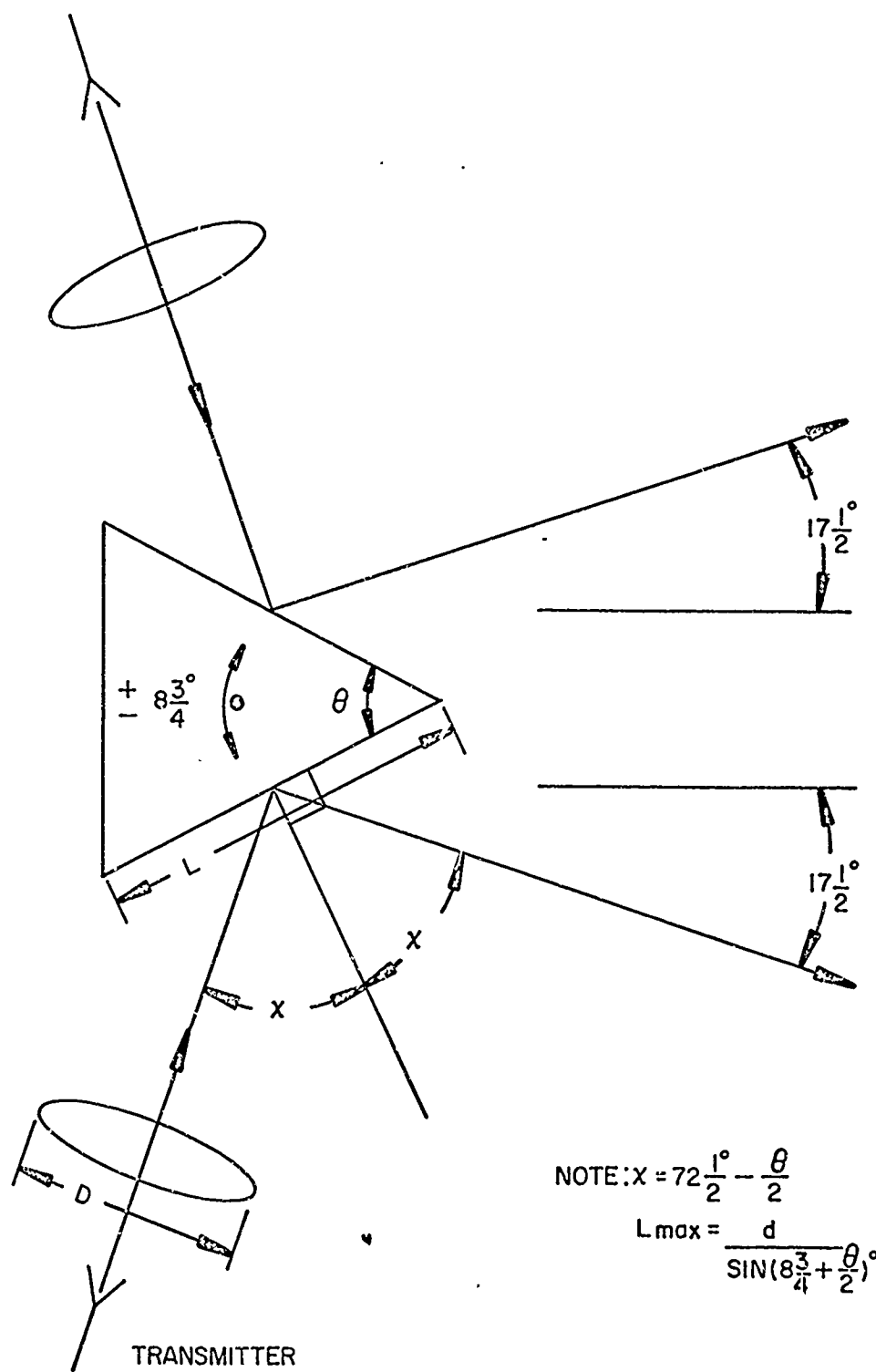
Another approach to the problem exists in the motion of a plane reflector. This could actually be two reflectors taking the

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shape of a prism as shown in Figure 1. The beams would be first
collimated by a lens or parabola of the desired aperture size and
then would impinge immediately upon the steering reflector. In
the center, or neutral position, the beams would each be $17\text{-}1/2^{\circ}$
displaced from the bisector of the wedge. A $\pm 8\text{-}3/4^{\circ}$ pivot of the
reflector would then provide the two 35° sectoral coverages. The
angle of incidence and hence the length of the reflector sides would
then be determined by the wedge angle. For example a 90° wedge
would require a side of about $1\text{-}1/4$ times the aperture diameter
where a 60° wedge would require 1.6 times d. The height of the
wedge remains constant at d. Integrating the two reflectors in a
structure of this sort leads immediately to a quite rigid assembly
and eliminates the need for providing synchronized movement of
two separate reflectors.

A major drawback to this approach is the space required in
the direction approximately normal to the beam. This requirement
makes the system unattractive for a helicopter-borne operation.

A very attractive approach to steering two beams simultaneously
involves the use of a Luneberg lens. The focusing properties of
this graded dielectric constant sphere are well known. As sketched
in Figure 2, the rays through the sphere are sectors of ellipses of
varying eccentricity through all ranges from the limiting case of
the circle on the outermost ray to the straight line through the center.
If now the sphere is bisected by a ground plane, the focusing properties
are unchanged; the focal point is merely reflected to a new position
on the periphery of the sphere as indicated. Now steering can be
accomplished by moving either the feed or the lens; without the
ground plane, the feed must be moved. Since the feed horns required
are fairly small, the aperture blockage is roughly comparable to a

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$\pm 8\frac{3}{4}°$

θ

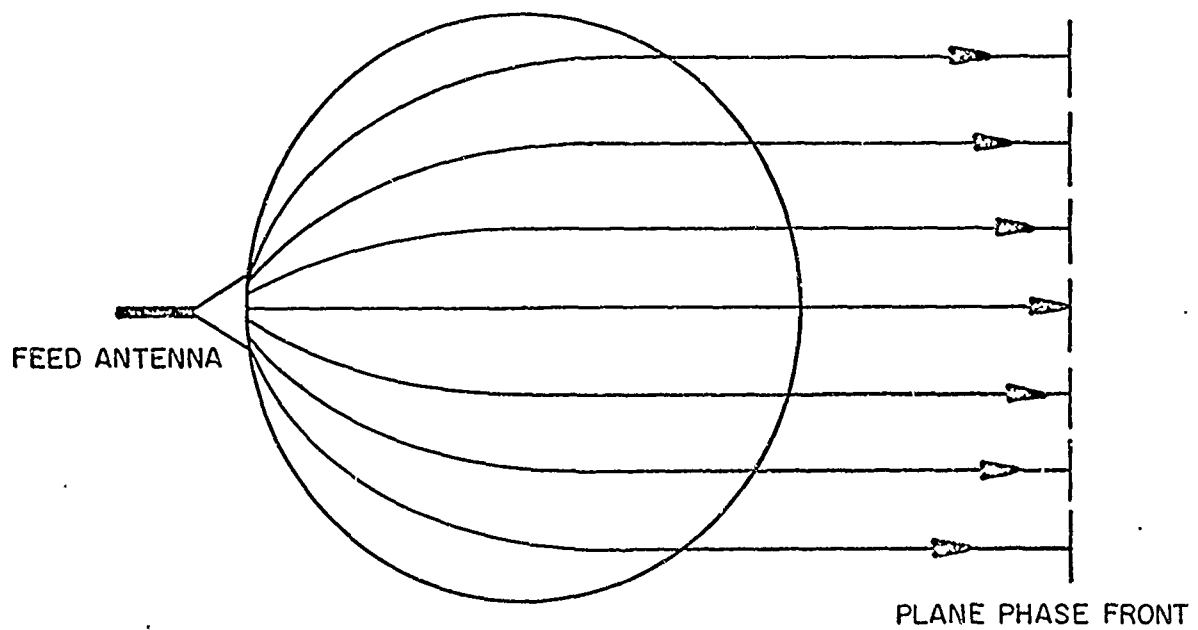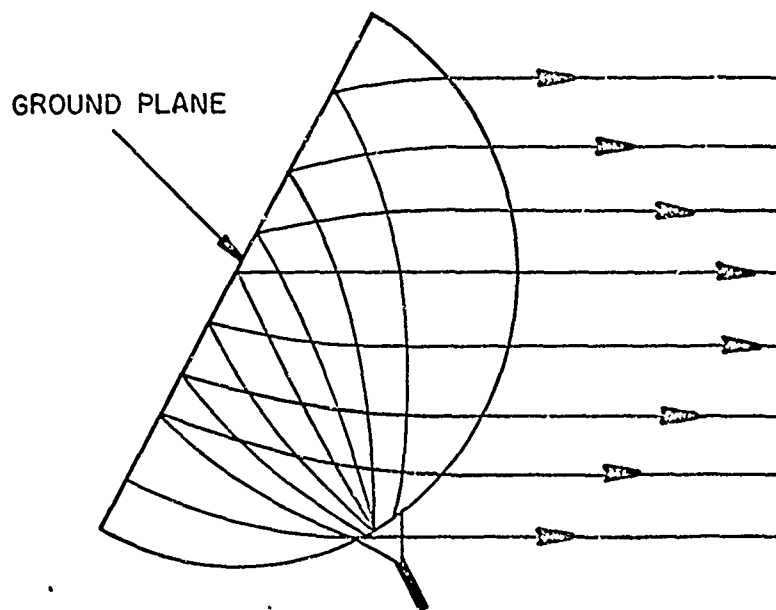$17\frac{1}{2}°$

$17\frac{1}{2}°$

L

X

X

D

NOTE: $X = 72\frac{1}{2}° - \frac{\theta}{2}$

$$L_{max} = \frac{d}{SIN(8\frac{3}{4} + \frac{\theta}{2})°}$$

TRANSMITTER

FIG. I — OSCILLATING WEDGE GEOMETRY

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FEED ANTENNA

PLANE PHASE FRONT

(A) LUNEBERG LENS

GROUND PLANE

(B) STEERABLE HEMI-SPHERICAL LUNEBERG LENS

FIG. 2 - LUNEBERG LENS CONFIGURATION

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parabola, and the penalties would not be too severe if a second feed were added to provide a beam directed 35° away from the one indicated. Then rocking the lens about an axis in the ground plane through angles of $\pm$ 8-3/4° would give the two beam coverage of a 70° sector with a quite constant beam shape.

A Luneberg sphere of 36" diameter for 10 GHz is currently available weighing only 75 lbs. The hemisphere with a rigid ground plane could undoubtedly be made to be of that order and perhaps lighter. So the problem of steering the lens itself would not be a physically formidable problem. In this way, all the waveguide components could remain fixed without even the requirements of rotary joints.

Thus, with this approach in mind, a preliminary study was undertaken to investigate feasibility of the 35 GHz potential. Although the concept remains attractive, the material problems are as yet unresolved for the millimeter wave frequencies and apertures of this size. The report will show approaches using one or two step approximations to the Luneberg lens which are suitable for apertures giving of the order of 30 dB of gain. No practical solutions were found, however, which are compatible with the specific operational requirements associated with this study.

2. THE LUNEBERG LENS AND ITS FABRICATION

2.1 Lens Design

The illustration of figure 2-A is the most generally accepted concept when the term Luneberg lens is applied. Achievement of such a lens requires that the dielectric constant of the material vary in accordance with the relation $n = \sqrt{2 - r^2}$ where r is the normalized radius varying from $0 - 1$.

Although conceptually and theoretically attractive, this leads to a rather impractical material requirement. Hence, over the past 20 years there has been a continuing search for approximations or modifications on this design which will lead to more tractable types of fabrication.

A quite comprehensive bibliography of the lens design work is given by Rudduck and Walter[1] for the period through 1960. These designs have included stepwise approximations to the $\sqrt{2-r^2}$ index using many concentric spherical shells, geodesic equivalents using a parallel plate waveguide, other approaches to a surface wave lens, etc. Of the many types on which design data are available, many are limited to a two dimensional system and are inappropriate for the application being considered here.

The group which has the greatest potential for this specific program are those approximations which can be classified as radially symmetric. These can be multi-step, two step or even one step approximations to the normal Luneberg configuration as discussed below.

2.1.1 Radially Symmetric Lenses

The simplest of all lenses in this category is the homogeneous dielectric sphere. To be useful as a millimeter wave steerable lens, the focal point must be external to the sphere and

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so the ray diagram of interest takes the form of Figure 3. For this
lens to be used as an antenna, one would wish simultaneously to
satisfy two conditions: that the exit ray BC emerge parallel with
the axial rays OD, and that the electrical path lengths FC and FD
be equal to achieve a planar phase front. These conditions are not
independent and cannot, in general, be satisfied precisely. They
can, however, be met to a quite good approximation if one is interested
in antennas with gains of the order of 30·dB.

The condition for paraxial emergence is readily
obtained by inspection of the figure and the use of Snell's law. It is
clear that what is required is that $2(\psi_i - \psi_r) = \theta$. Further, assuming
$n_1 = 1$ then $n_2 \sin \psi_r = \sin \psi_i$. We can also obtain readily from the
sine law the relation $\sin \psi_i = \dfrac{f+r}{r} \sin \theta$. From these three relations
we can quickly arrive at an estimate of the requirement on n_2. Since
these relations must hold for small angles where $\sin\theta = \theta$, etc.,
we may write

$$\theta = \frac{r}{f+r} \; \psi_i = 2 \psi_i \left(1 - \frac{1}{n_2}\right)$$

which, on solving gives

$$n_2 = \frac{2(f+r)}{2f+r}$$

Hence, if we wish the focal point to be exterior to the lens ($f > o$), the
refractive index must be in the range of $n_2 < 2$, a condition which
can be readily met.

It is also apparent, however, if one does not
make the small angle approximations, one will arrive at an expression
for n_2 which is dependent upon θ. Hence for some fixed n_2, there
will be an aberration in the output, much like the standard spherical
aberration.

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Examination of the criteria for the phase relationship at the output leads to a more cumbersome expression. For the representation of Figure 3, straightforward geometrical considerations show that the lengths of the line segments can be written as

$$\overline{FA} = (f+r) \cos \theta - r \cos \psi_i \quad .$$

$$\overline{AB} = 2r \cos \psi_r$$

$$\overline{BC} = r [1 - \cos (2 \psi_r + \psi_i - \theta)]$$

and the requirement of uniform phase states that $FA + BC + n_2 AB = f + 2n_2 r$. Small angle approximations lend no insight here as they simply lead to an identity. The expression for n_2 solved becomes extremely cumbersome, quickly indicating that some computer analysis could be desirable.

Before finding a reference where the computer approach had indeed been followed, this investigation had pursued the single sphere and the next step for correction (as indicated in Figure 4) on a graphical and trial and error approach to see roughly the magnitude of the errors involved. The two step sphere was simply treated as an iteration of the first one where θ' was defined as $\theta' = \theta - (\psi_i - \psi_r)$, being the elevation angle toward the inner sphere. The problem was no longer treated under the constraint of requiring that the output ray be paraxial. Values were assumed for various parameters and solution was made for the error in angle which would exist in the ray as a function of the incident angle θ. This error was calculated for θ taken in 5° steps from 0 to 45°. When the calculation was finished, an adjustment was made in the parameters to correct the single worst error, and the computations repeated. This process was itself repeated a few times to see if the approach led to some type of convergence and it did appear to do so.
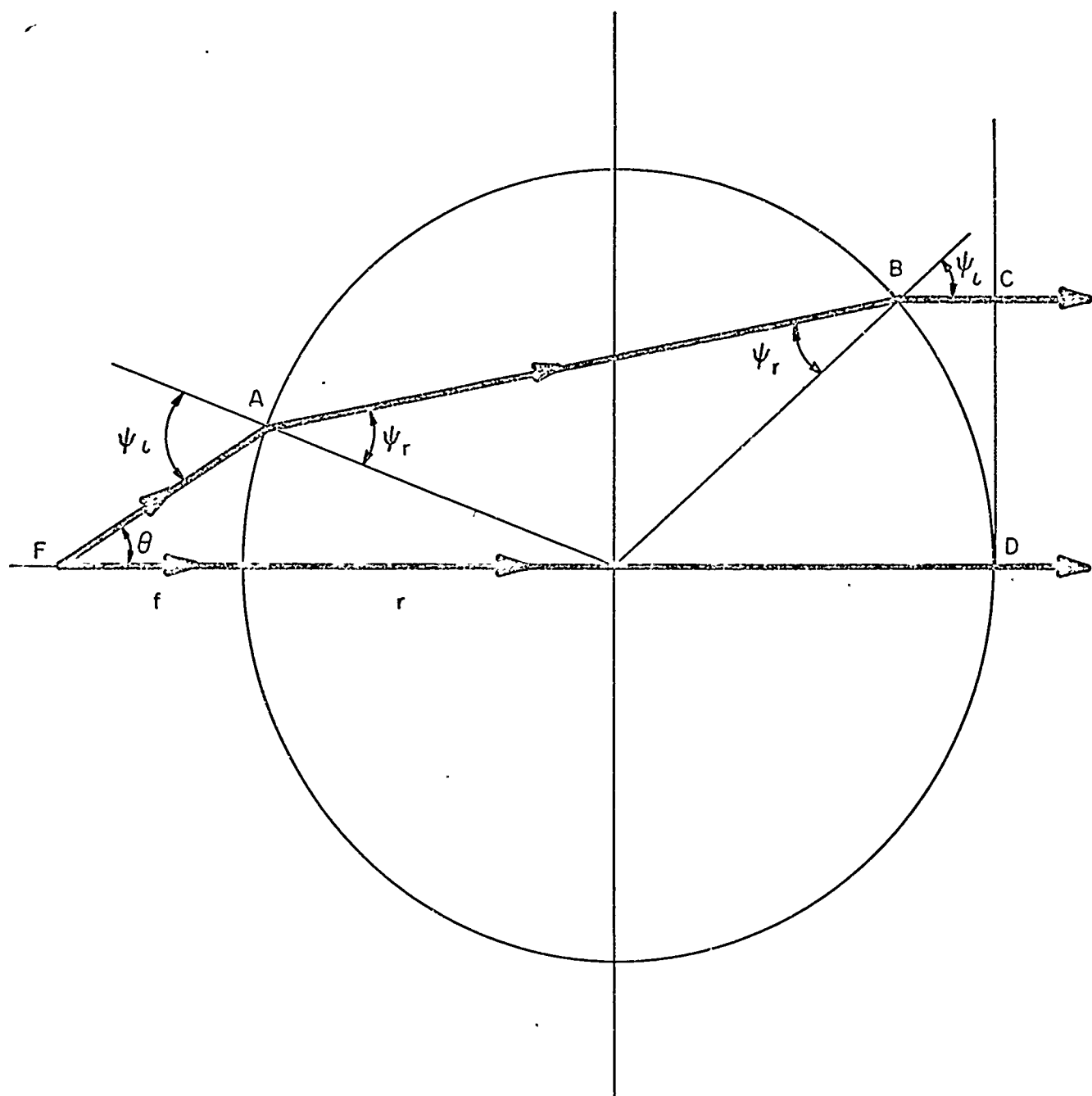
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ψ_ι C

ψ_r

B

A

ψ_ι

ψ_r

F θ

f

r

D
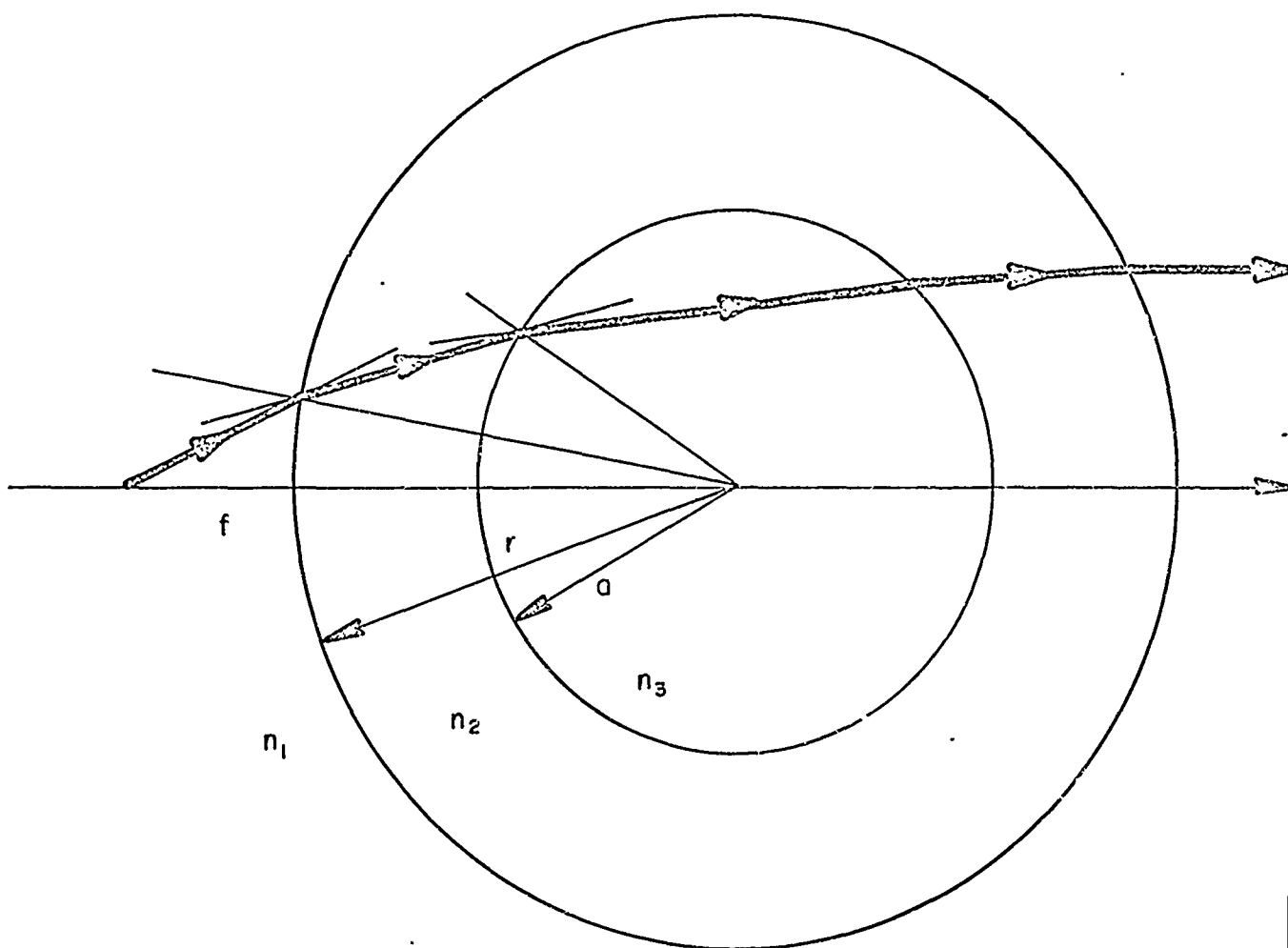
FIG. 3 - RAY GEOMETRY IN A HOMOGENEOUS SPHERE

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FIG. 4 - RAY GEOMETRY FOR TWO SHELL SPHERE

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The starting point was influenced by having examined the homogeneous sphere case with similar calculations. Hence the initial parameters picked were $\frac{f+r}{r}$ = 1.1, n_2 = 1.6 and a/r = 0.5. This in turn led to a choice for n_3 of about 1.7. In succeeding trials, the focus, and the radius of the center sphere were adjusted to reduce the larger errors, and after not too many times around, the parameters had come to be a/r = .4436, n_2= 1.61, n_3 = 1.63, and $f+r/r$ = 1.111. With these values the deviations from paraxial at the angles calculated averaged less than 1/2 degree, in magnitude, ranging from -26' to -43'.

It was at this point that the existence of the computer solutions was discovered, and the hand calculations discontinued. Two figures have been reproduced here from the report by apRhys[2]. These figures present the requirements on the refractive index if one requires paraxial rays and permits an inhomogeneous central sphere with a homogeneous outer shell. Since the focal point is taken to be outside the sphere, the "no shell" case does not go up to $\sqrt{2}$ as the "normal" Luneberg lens. But one can see in Figure 5, there exists a region where the refractive index can be almost constant, as shown more clearly in Figure 6. We have added to Figure 6 the line indicating the approximation arrived at by the previously mentioned calculation, and it is apparent why this led to reasonable accuracy in the output rays.

Figure 7 shows however that if one is trying to use two homogeneous materials for the approximation, it might be better done with the 1.95 and 2.1 combination, with the higher index material as the outer shell.

Mentioning these numbers, however, gives rise immediately to the question of materials. The higher dielectric

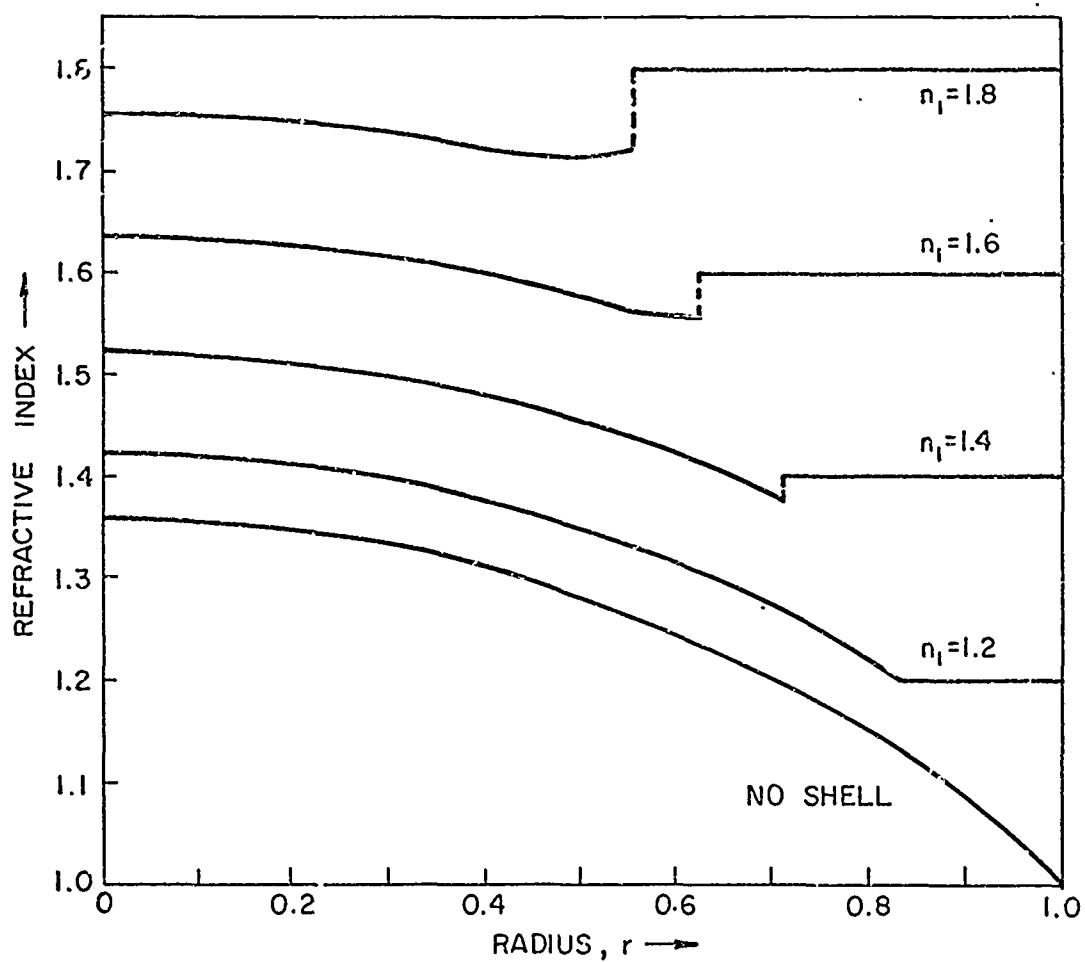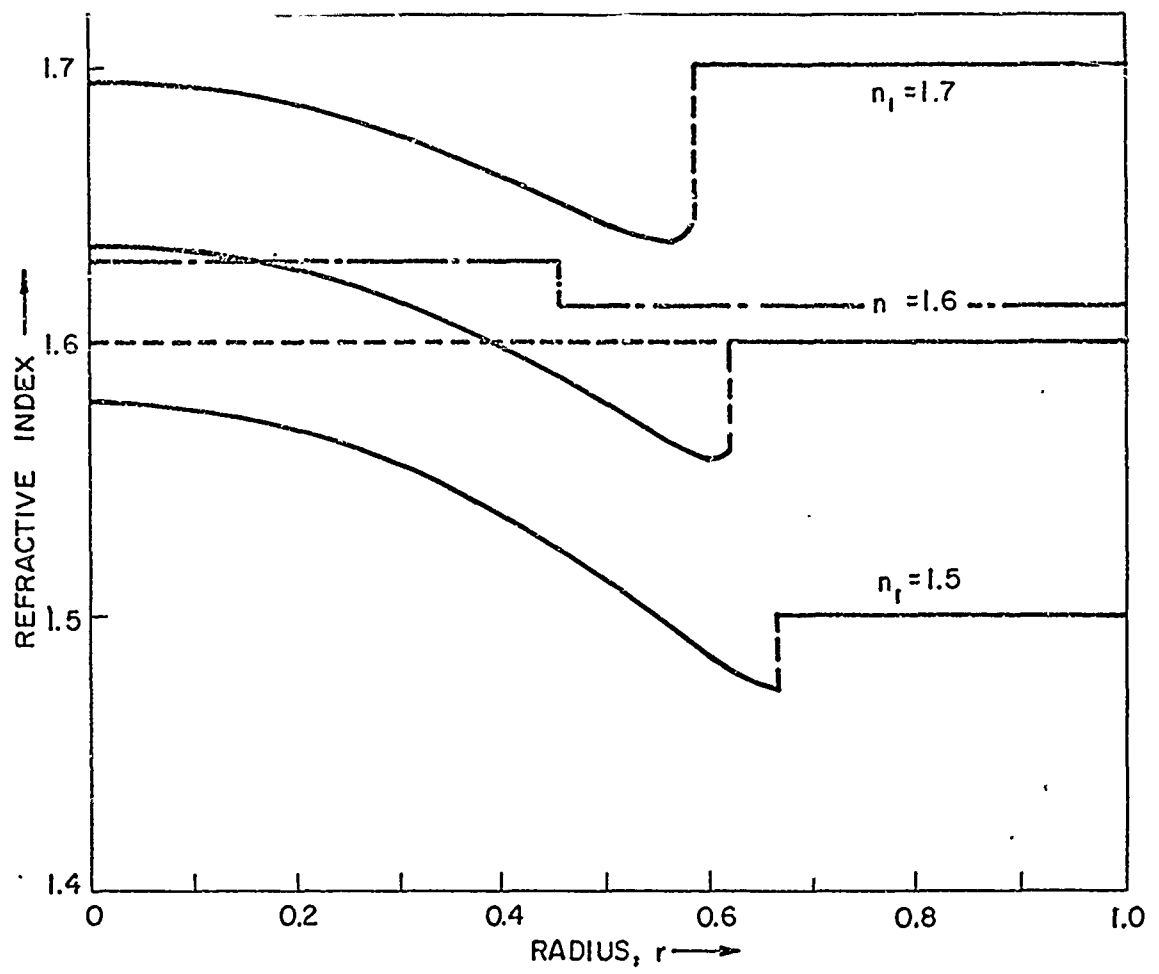FIG. 5 REFRACTIVE-INDEX DISTRIBUTIONS OF LENSES HAVING r = 1, f + r = 1.1

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FIG. 6 REFRACTIVE INDEX DISTRIBUTIONS OF LENSES HAVING r=l,f+r=l.l

13
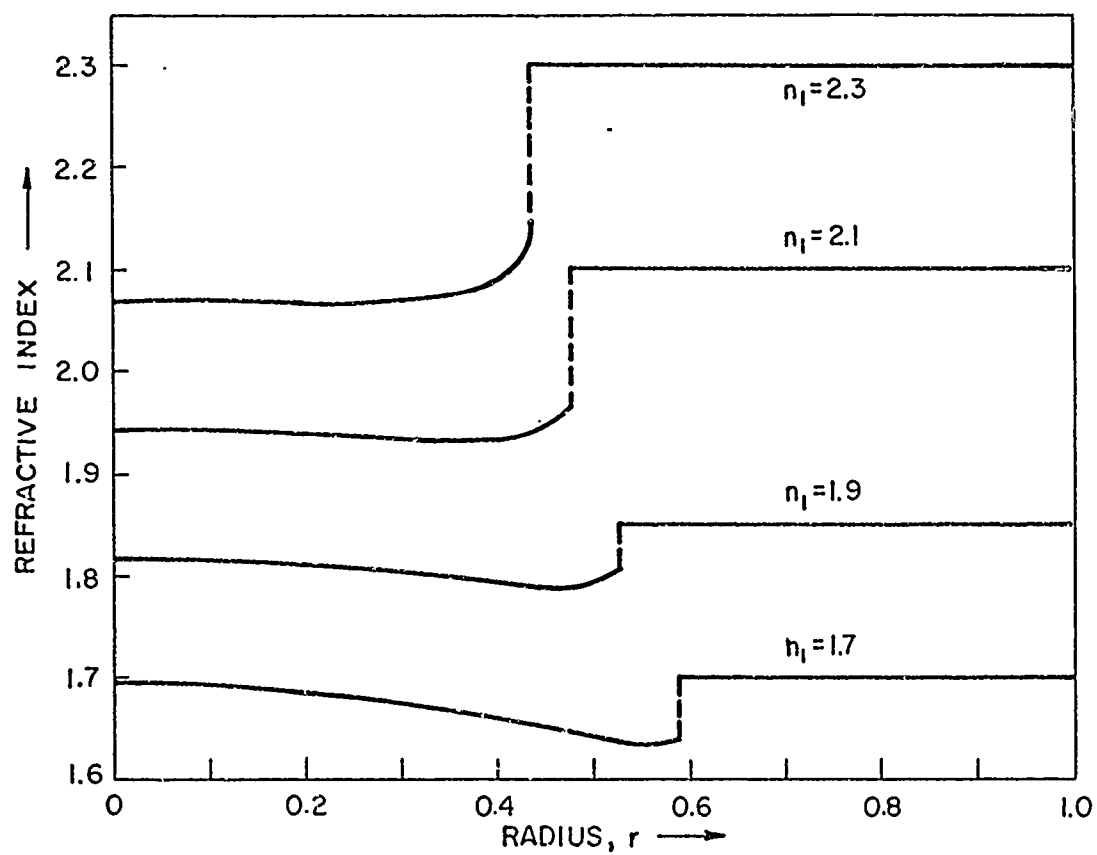
FIG.7 REFRACTIVE-INDEX DISTRIBUTIONS OF LENSES HAVING r=1, f÷r=1.1

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constants and light weight are generally incompatible at millimeter wavelengths, and one can foresee immediately a materials problem if large apertures are being considered. The aforementioned refractive indexes agree well with fused and crystal quartz, but the latter do not agree well with 36" diameter lenses.

2.2 Lens Fabrication

In attempting to approximate a varying dielectric constant through a sphere at lower frequencies, at least two approaches have been successfully used. The first of these was produced by Emerson and Cummings as reported by Peeler and Coleman[3]. This was the 10 step shell approximation using foam plastic materials to form an 18" diameter sphere. The lens worked well at 3.2 and 1.8 cm wavelengths (although the sidelobe level was deteriorating in the latter case) but at 8 mm the reference states "...it did not focus for any feed position at this wavelength." This is probably due to a combination of foam cell size, and wave trapping between shells. Whatever the mechanism, the material to date seems inappropriate for use at millimeter wavelengths, although the concept is no doubt still valid.

A second approach was put forth by the Armstrong Cork Co.[4] This involves the fabrication of a continuously graded dielectric constant in cylinder form. The cylinder is then converted to a sphere using the approach illustrated in Figure 8. The variation in dielectric constant is achieved through the use of metallic slivers imbedded in the low density foam in the forming process. This combination of a low density foam and an artificial dielectric leads to an even more severe problem at short wavelengths, since the loss tangent of the material is increasing rapidly in addition to the standard problem of foam cell size. Forty-four inch diameter
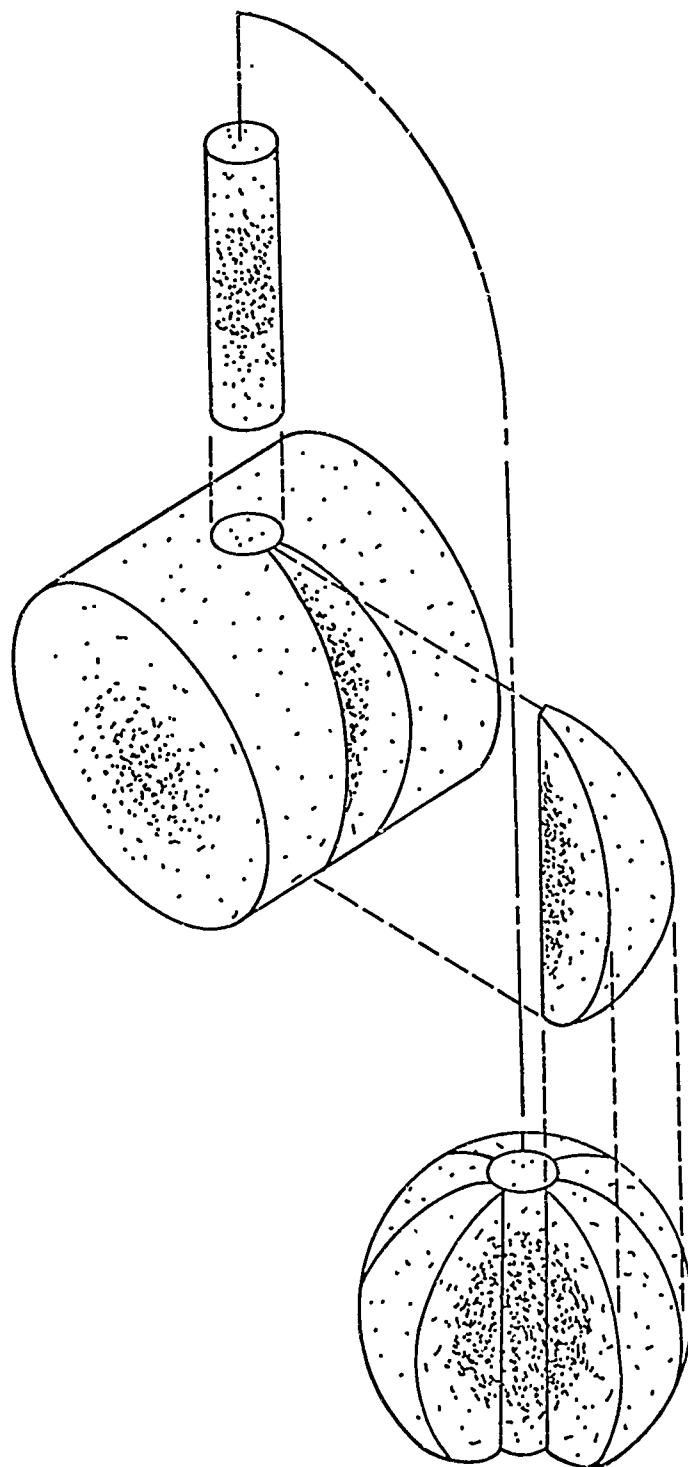
FIG.8 -ASSEMBLY OF FOCUSING SPHERE FROM A FOCUSING CYLINDER.

spheres have been made by this technique, but no test data is available above 10 GHz.

A two shell quartz sphere and a homogeneous Rexolite sphere were fabricated and data reported in Reference 3 for 70 GHz operation. The measured data agree well with the theory. For the case of the homogeneous sphere, however, the theory will show a distinct limitation on aperture size. Defining $K = 2\pi r/\lambda$ where r is the sphere radius, the homogeneous sphere has its maximum gain (approximately 35 dB) when $K = 150$. Larger diameters lead to decreased gain. This investigation was considering a K of the order of 350, precluding the single homogeneous sphere.

The data and theory presented for the two step quartz lens however, indicate it would still give good performance for $K = 300$. Further a purely theoretical evaluation of a two material lens with indexes of 3.507 on the outer shell and 2.096 on the center sphere permit extrapolation to $K = 30,000$ providing a theoretical gain of some 90 dB. No doubt other factors would enter which would limit the practically achievable gain to a more conceivable 70 dB.

The significant point here is that once again the problem is one of finding the material with which to fabricate the device. Working with two steps instead of 10 should significantly alleviate much of the fabrication problem. For the present, however, one is limited to working at extremely short wavelengths where one can consider the use of such materials as quartz (such as a 4" sphere at 300 GHz as a 50 dB gain antenna), or at much longer wavelengths where foam and artificial dielectrics can be used successfully.

3. CONCLUSIONS AND RECOMMENDATIONS

The idea of a radially symmetric antenna as a steerable receiving or radiating aperture is sound. The principles of design and fabrication are well established and experimentally verified both at microwave and millimeter wave frequencies within certain limitations on gain characteristics.

The requirements of a three foot lens in combination with a 35 GHz frequency are unfortunately not compatible with the materials which are currently available although many other combinations would be workable. It is recommended then that further pursuit of this approach be held in abeyance pending some unforeseen development in synthetic materials.

As more fruitful alternatives in the meantime, we would recommend investigation of electronic steering techniques. At least two of these seem worthy of mention. The first is a somewhat modified phase shifter technique, abetted by the fact that steering is required in only one plane.

This last fact means that the array could be comprised of sectoral horns or hog horns, providing a uniform phase distribution along one axis and permitting the phase tilt to be adjusted along the other axis. When one is considering 100λ apertures, this saving on the element number is certainly significant. The usual picture of a filled steerable array is made up of elements spaced on the order of one-half to six tenths of a wavelength, so we have reduced from some 30,000 or more to the order of 175 with step one.

Further reduction of the element number may still be possible, however, depending upon other requirements in the system. A current 35 GHz development program at ADTEC will result in a feasibility model of a fully steerable antenna (i. e., both azimuth

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and elevation control.) The system requirements here are for approximately 25° steering capability. An additional benefit was that any grating lobes which occurred outside of this region of interest were of little consequence. Hence the element spacing could be relaxed. The array remains fully filled, but each radiating element is a pyramidal horn (see Figure 9). The element spacings are approximately 2.2 λ so that the peaks of the grating lobes fall well outside the region of the main beam scan for any steering position. One gets some further benefit from the fact that the overall antenna pattern is the product of the element factor and the array factor. Hence the magnitude of the grating lobes are reduced by the directivity of the horns. (There is, of course, a limit to the extent to which this factor can be beneficial, since the steered main beam is likewise affected by the element factor. This is a compromise which must be considered in the design.)

Hence for the case under consideration here, the figure of 175 elements may be amenable to some reduction. For example the grating lobes which might arise as a result of larger spacing might be removed from the problem by appropriate use of absorbing material in the vicinity of the antenna. In the current development program a 16 x 16 array could be replaced with a 7 x 7. A reduction of this extent is not quite practical with a 35° steering requirement. However it is conceivable that a reduction of the order of over 1/2 would be practical permitting steering of a 100 λ aperture with 60 to 75 elements. Some computer solutions of the far field patterns would be beneficial in making such a decision.

The use of electronically steerable systems at 35 GHz can be contemplated now with the developments which have recently occurred with ferrite phase shifters. Latching ferrite devices are now practical
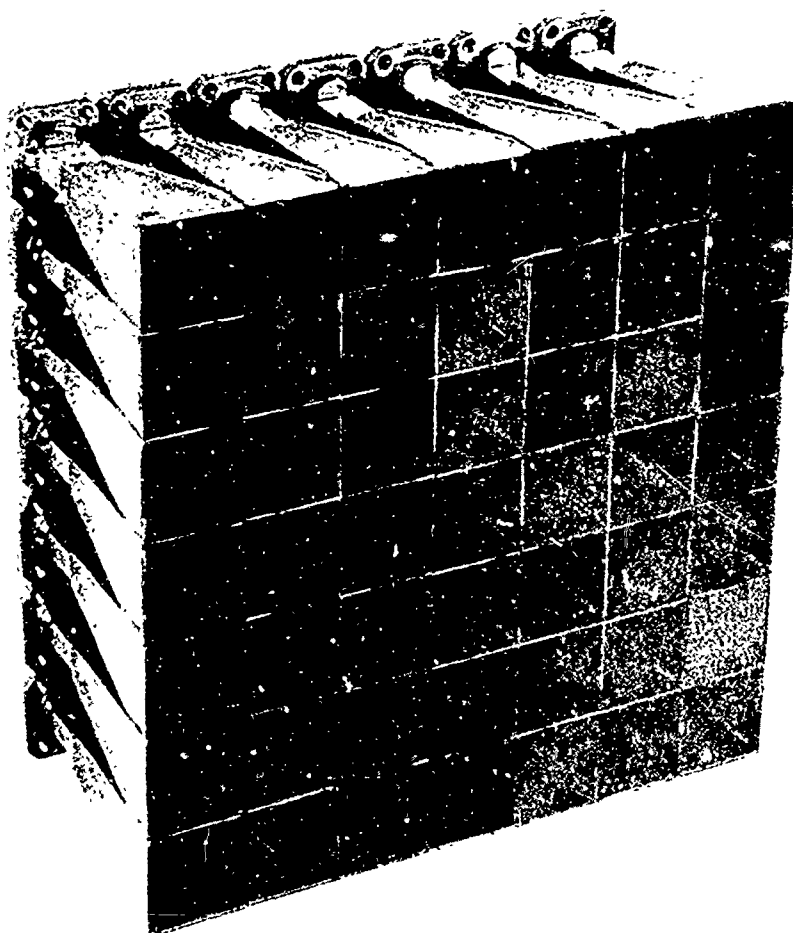
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Figure 9   Aperture of Developmental 35 GHz Steerable Antenna

with reasonable insertion loss.[5] With a modest amount of develop-
ment, analog phase shifters could also be brought to a suitable size
for array operation. The latching devices, however, have a large
advantage in terms of associated control circuitry. The logic needed
to control three or four bit digital devices is very readily achieved
with current integrated circuit techniques. The driver requirements
are modest, and the power drain is reduced since no holding currents
are required.

In short, it is felt that the development work necessary to
produce an antenna of this type is reasonably predictable, and the
principles are established and will shortly be experimentally verified.
None of these statements are true concerning the search for a proper
material for a radial lens.

A second approach to the steerable antenna solution would
involve a completely new system concept. Although it would resolve
the antenna steering problem, it would substitute some rather signi-
ficant ones of its own. We are speaking here of the use of a nonresonant
slot array antenna. This type of antenna can be steered in one dimen-
sion by a frequency scan. The elevation angle of the beam (θ) measured
from the face of the antenna is given by the expression $\cos \theta = c/v_p$,
i.e., the ratio of the velocity of light to the phase velocity in the
waveguide.

That the necessary steering capability can be achieved has
been demonstrated by Jones and Shimizu.[6] Their antenna, in X-band
waveguide was operated from 7 to 11.5 GHz with excellent agreement
between experiment and theory in beam shape and steering angle.
This could be scaled to the region around 35 GHz with an appropriate
choice of a non-standard waveguide size. Some sample calculations
were made using the standard frequency range of RG-96/U waveguide,

but reducing the dimensions to increase the dispersion in the range. Thus with a waveguide whose broad dimension would be 0.238", we find θ at 26.5 GHz to be 70° 20', and at 43.5 GHz, $0 = 34^{\circ}$ 30'. This is a scan of about 36° using a ± 8.5 GHz deviation from 35 GHz.

Considering that this antenna might be used as a radiometer receiving aperture, the problems raised are several. First, the steering would have to be achieved by sweeping the mixer local oscillator over this range. This requirement does not appreciably extend the present state-of-the-art in swept frequency sources. Next, the mixer would have to operate over this range in an instantaneous fashion. This <u>does</u> push the mixer technology from its present position. The chances are that such a mixer would not be so sensitive as one with a narrower instantaneous bandwidth requirement. Third, the radiometer would be required to work in a single channel mode to avoid the formation of two beams, and the bandwidth would directly influence the effective beamwidth of the antenna.

Whether these considerations offset the advantages of the rather simple steering mechanism will be determined largely by system sensitivity requirements. This would require sacrificing at least 3 dB through the loss of double channel operation, and no doubt some more in mixer efficiency and bandwidth. The bulk of the development work involved is in the mixer aspect. The antenna itself is not trivial, but seems to be a quite reasonable component development for this frequency range. In this case, as in the preceding one, the necessary work and the approaches available are more clearly defined than in the materials problem.

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13. ABSTRACT

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